FFAG Lattice Without Opposite Bends

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INTRODUCTION

A future "neutrino factory" or Muon Collider requires fast muon acceleration before the storage ring. Several alternatives for fast muon acceleration have previously been considered. One of them is the FFAG (Fixed Field Alternating Gradient) synchrotron. The FFAG concept was developed in 1952 by K. R. Symon (ref. 1). The advantages of this design are the fixed magnetic field, large range of particle energy, simple RF; power supplies are simple, and there is no transition energy. But a drawback is that reverse bending magnets are included in the configuration; this increases the size and cost of the ring. Recently some modified FFAG lattice designs have been described where the amount of opposite bending was significantly reduced (ref. 2, ref. 3).

Muon acceleration needs to be very fast, because of the short muon lifetime. It is desirable to accelerate in as few turns as possible, subject to the limitations of RF capabilities. To accelerate muons from 5 GeV to 15 GeV, we may use as few as 10- 15 passes. This eases a lot of constraints on synchrotrons, like higher order betatron resonances; even the chromaticity should not be as important as normally. We present a first attempt to make an FFAG lattice without opposite bends to be used for muon acceleration within 5-15 GeV energy range.

MAJOR GOALS

The value of the dispersion function as well as the betatron functions through the synchrotron should be very small to permit accepting a large range of momentum of the circulating particles and keep within the aperture. The limitations on betatron functions are determined by the aperture size. If the aperture is assumed to be 70 mm (+-35 mm) then for the momentum offsets of:

$-0.5 < \Delta p/p < 0.5,$

the dispersion function ($\Delta x = D_x * \Delta p/p$) should be:

$D_x < 70$ mm,

between muon energies 5-15 GeV where the central energy is equal to 10 GeV.

The particle's momentum is assumed to accelerated by "distributed" accelerating cavities, as it travels through the synchrotron. The momentum increases from one "cell" to the next. We desire a lattice which allows particles within the momentum range of $-0.5 < \Delta p/p < 0.5$ to be stable without crossing integer tunes or resonances.. The necessity of dipoles with reversed field, as in the original FFAG design of K. R. Symon, is avoided by applying our previously reported FMC (flexible momentum compaction) method.

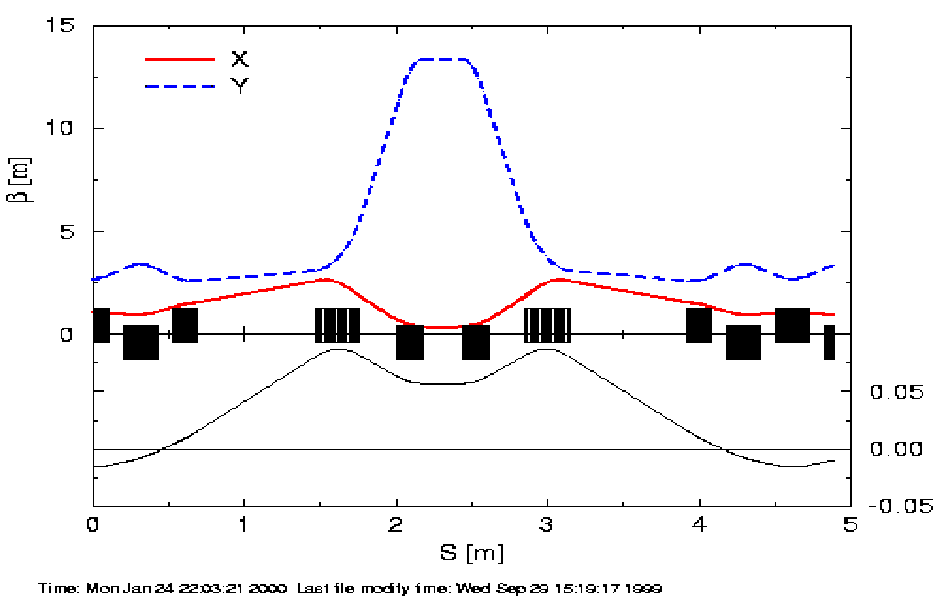


Figure 1 represents the betatron functions through one cell . Combined function magnets are presented as boxes.

THE FIRST EXAMPLE

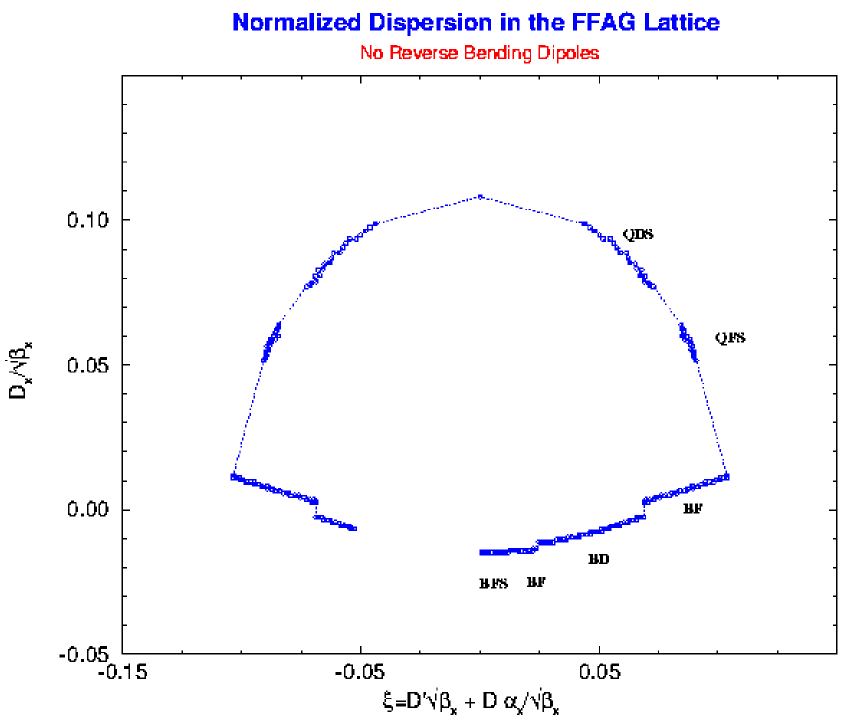
A first attempt at a FFAG lattice without opposite bending is presented in fig. 1. The cell contains:

Major bending elements, including combined function magnets with small gradients (presented at the left and right side in figure 1), where all betatron functions, including dispersion, have small values. (β_x<0.3 m, β_y < 0.55 m, D_x > -0.03 m).

A doublet QFS - QDS configuration (presented in the central region in fig. 1) consists of strong horizontally focussing QFS quadrupoles and a combined function magnet with vertical focusing. The maximum value of the dispersion function occurs in the middle of the of the focusing quadrupole QFS. The normalized dispersion space is defined by the Floquets' coordinate transformation as:

$$\zeta = \frac{D_x}{\sqrt{\beta_x}}, \qquad \text{and} \qquad \chi = D^{'}\sqrt{\beta_x} + \frac{\alpha_x D_x}{\sqrt{\beta_x}}.$$

The top of fig. 2 represents the middle position of the betatron functions (as presented in fig. 1). Positions of the magnets are represented in fig. 2 by their names. At the bottom of fig. 2 is the position of the center of the combined function magnets with the largest bending angle. A vector from (0.0) to any point of this graph represent a square root of the amplitude function H.


Normalized Dispersion in the FFAG Lattice
No Reverse Bending Dipoles
QDS
QFS
BF
BD
BFS
BF
0.10
0.05
0.00
-0.05
-0.15
-0.05
0.05
$D_x/\sqrt{\beta_x}$
$\xi = D'\sqrt{\beta_x} + D\,\alpha_x/\sqrt{\beta_x}$

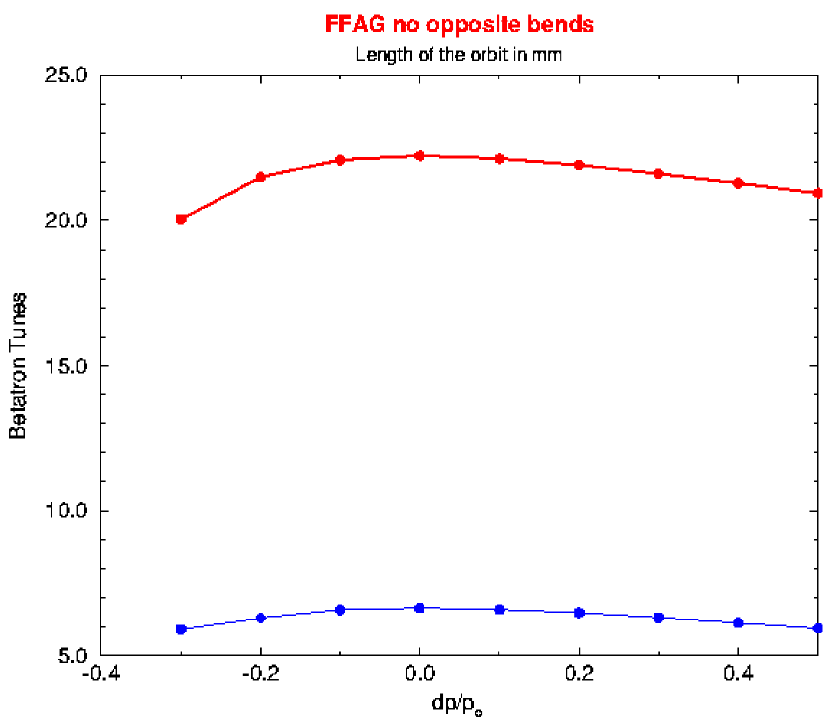

FFAG no opposite bends
Length of the orbit in mm
25.0
20.0
15.0
10.0
5.0
-0.4
-0.2
0.0
0.2
0.4
Betatron Tunes
dp/p_o

Figure 3 shows the tune dependence on momentum. At a momentum of $\Delta p/p$=-0.3 it is clear that the tune is very close to an integer value. As was noted above there will be only 10 –15 turns of the particles around the ring. If the particle starts with 0.7 p_o , where p_o represents the central value of momentum (which corresponds to energy of 10 GeV), immediately after few cells it would gain in momentum. The betatron tune for these particles would not represent unstable conditions.

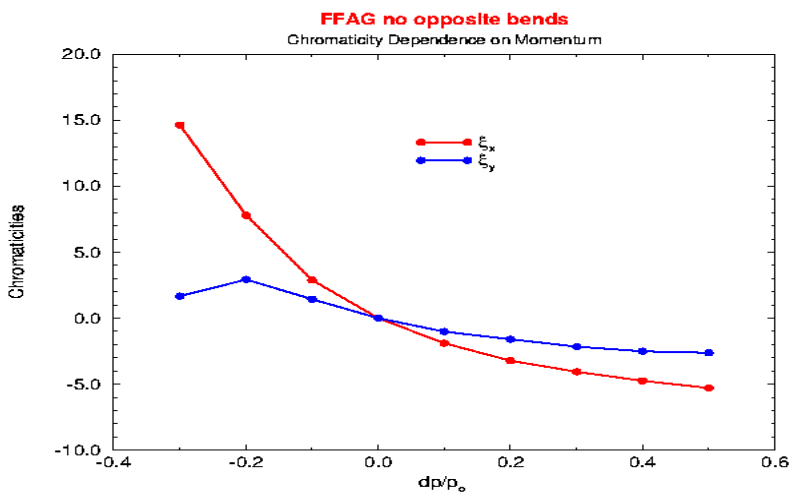


Figure 4 represents the chromaticity dependence on momentum of our first example. Again the particles with negative momentum offset of $\Delta p/p$=-0.3, will not go through unstable conditions as soon as they start orbiting around the synchrotron and gaining momentum kicks from the RF cavities.

CONCLUSIONS

The first example of an FFAG lattice without opposite bends shows promising results. It looks as if it may be possible to design an FFAG lattice which covering a momentum range $-0.5 < \Delta p/p < 0.5$, where even the particles with large momentum offsets have stable motion. The largest value of the difference in the path lengths of particles with different momenta, in this example, is of the order of 60 mm. This problem needs additional attention.

REFERENCES

1. K. R. Symon, "The FFAG Synchrotron – MARK I", MURA-KRS-6, November 12, 1954, pp. 1-19.
2. R. Ueno et. all, "Multi Orbit Synchrotron with FFAG Focusing For Acceleration of High Intensities Hadron Beams", PAC 99, New York, 1999, 2271-2273.
3. P. F. Meads, Jr., "A Compensated Dispersion-free Long Insertion for an FFAG Synchrotron", PAC 93, Proceedings of the 1993 Particle Accelerator Conference, Vol. 5 of 5, Washington D.C. , pp. 3825-3827.